



United States Department of the Interior

GEOLOGICAL SURVEY  
EROS Data Center  
Sioux Falls, South Dakota 57198

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REPLY REFER TO:

OAB4-100

April 26, 1984



Memorandum

To: Technical Officer

From: Principal Investigator AN 31

Subject: Quarterly Report: Landsat 4 Investigations of Thematic Mapper and Multispectral Scanner Applications (PCN902-91548; S-10757-C)

1) Problems

No problems occurred this quarter.

2) Accomplishments

- a) Geologic anomalies seen on the Death Valley thematic mapper (TM) scene were located in the field. Similar anomalies were anticipated to be present and subsequently found on the TM scene covering an area north of Flagstaff, Arizona. The latter site was also field verified and samples from both sites were submitted for analysis to the laboratory in Phoenix, Arizona.
- b) A comparison of the information content of a digitally enlarged TM image and a digitized black-and-white aerial photograph of the same area is being carried out. A northern Virginia TM subscene of the Dulles-Reston area was digitally enlarged 7X, smoothed with a 7 by 7 low pass filter, edge enhanced with a 15 by 15 box filter, and registered to the digitized photograph. Approximate pixel resolution was four meters. The "blocky" appearance of the TM subscene suggested that a smaller (perhaps 5 by 5) box filter for edge enhancement would produce a more correct image.
- c) The Dulles-Reston subscene was also compared to a simulated SPOT image of the same area for spectral content. The analysis indicated that the difference in "color" information present in the three equivalent TM bands was not very different from the three SPOT bands. High correlation between the equivalent bands of the two sensors and little, if any, new information added from band-to-band comparisons may have been due to the small size of the test area and a narrow range of cover types.

- d) A paper on TM image processing was presented at the ASP Annual Meeting in Washington, D.C. The paper covered some of the techniques used to 1) reduce the amount of data that needs to be processed and analyzed by either using statistical methods or by combining full resolution products with spatially compressed products, 2) digitally process small sub-scenes to both improve the visual appearance of large scale products and to merge different resolution image data, and 3) evaluate and compare the information contents of the different three band combinations that can be made using TM data. Results from the use of techniques for assessing information content indicate that for some applications, the added spectral information over MSS is more important than the increased spatial resolution. This is because there is "new" information in the TM bands that were not part of the MSS system. For example, the potential use of two three-band TM combinations for extraction of soil moisture and ground water depth information in arid and semi-arid areas shows promise and warrants further research.
- e) The statistical information generated earlier from TM data for the Dyersburg and San Francisco areas was checked. The earlier results were found to be correct and have been added to the statistical/Optimum Index Factor (OIF) package with other TM image results. The San Francisco TM image has also been used to evaluate water enhancement methods developed for MSS data. The results were not as good as was expected because of the amount of noise (striping plus other high frequency noise patterns) that was present in TM band 1. In order to improve the results, it is necessary to go back to the step before stenciling (removal of non-water pixels) and use a second order convolution filtering technique to remove the noise before applying the stretch, smoothing, and color coding algorithms.
- f) Analysis of the Washington, D.C. TM image was requested by NMD in Reston. The statistical information was needed to generate OIF rankings and to perform selective principal component analysis on the data. The OIF technique ranked combination TM 1, 4, and 5 as number 1 and TM 1, 2, and 3 as number 20 (lowest).
- g) Black-and-white and color prints of processed TM data of the Silver Bell copper mine area were sent to General Electric (GE). GE requested, and NASA approved, use of some of the prints in their Landsat-TM brochure prepared for distribution during the March 1 launch of Landsat D.

### 3) Significant Results

Extensive work has been done using the Optimum Index Factor (OIF) for choosing TM band for color compositing or reducing the amount of digital data to be processed. See publication attached.

## 4) Publications

Chavez, P. Jr., Guphill S. C., and Bowell, J. A., Image Processing Techniques for Thematic Mapper Data: Proceeding of the ASP Spring Conference, Washington, D.C., March 1984.

## 5) Recommendations

None

## 6) Data Utility

None



Donald T. Lauer

Attachment

## IMAGE PROCESSING TECHNIQUES FOR THEMATIC MAPPER DATA

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### ABSTRACT

The Thematic Mapper (TM) imaging system onboard Landsat 4 provides new and much more comprehensive data than the data collected during the past 10 years by the Landsat multispectral scanner (MSS) system. A major challenge in working with the TM data is to process and analyze in an efficient manner the much larger volume of data resulting from the higher spatial resolution and the increased number of spectral bands. Processing techniques have been used on TM data over several sites to (1) reduce the amount of data that needs to be processed and analyzed by using statistical methods or by combining full-resolution products with spatially compressed products, (2) digitally process small sub-areas to improve the visual appearance of large-scale products or to merge different-resolution image data, and (3) evaluate and compare the information content of the different three-band combinations that can be made using the TM data. Results indicate that for some applications the added spectral information over MSS is even more important than the TM's increased spatial resolution.

### INTRODUCTION

The Thematic Mapper (TM) imaging system onboard Landsat 4, which was launched on July 16, 1982, provided new and much more comprehensive data than the data collected during the past 10 years by the Landsat multispectral scanner (MSS) system. The MSS system collects data in four spectral bands at a pixel size of approximately 80 meters, and the TM system collects data in six spectral bands having a pixel size of approximately 30 meters and one band (thermal) with a pixel size of about 120 meters (see Table 1 for a comparison between MSS and TM characteristics). A major challenge in working with the TM data over the MSS is to process and analyze in an efficient manner the much larger volume of data resulting from the increased spatial and spectral resolution.

TABLE 1  
LANDSAT-4 INSTRUMENT COMPARISON

MEASURE	MULTISPECTRAL SCANNER (MSS)	THEMATIC MAPPER (TM)
NOMINAL GROUND RESOLUTION	60 x 80 METER	30 x 30 METER
SWATH WIDTH	185 KM	185 KM
SPECTRAL BANDS (NM)	—	0.45 TO 0.52
	0.5 TO 0.6	0.52 TO 0.60
	0.6 TO 0.7	0.63 TO 0.69
	0.7 TO 0.8	0.76 TO 0.90
	0.8 TO 1.1	1.55 TO 1.75
	—	2.08 TO 2.35
	—	10.4 TO 12.6
A/D CONVERSION (BITS PER PIXEL)	6	8
APPROXIMATE NUMBER OF PIXELS PER SCENE (ALL BANDS)	32 MILLION	300 MILLION
DATA RATE	15 MBPS	85 MBPS

(TABLE FROM D. M. SMITH, 1982)

A variety of processing techniques have been used on TM data over several different sites to address three topics. The first topic is to reduce the amount of data that needs to be processed and analyzed by either using statistical methods or by combining full-resolution products with spatially compressed products. A second topic is to use digital processing on small sub-areas to improve the visual appearance of large scale products or to merge different-resolution image data. The final topic is to evaluate and compare the information content of the different three-band combinations that can be made using the TM data (excluding the thermal band).

The digital TM data used in this study was obtained from NASA's Goddard Space Flight Center through the EROS Data Center under two separate NASA TM investigations. The data was in P-tape format, with some radiometric and geometric corrections performed at Goddard (Salomonson and others, 1980). This paper does not deal with the geometric accuracy of the TM images and the interested reader is referred to papers by Blanchard and Weinstein (1980) and Wrigley and others (1983) for discussions on this matter.

#### Data Processing and Analysis

One of the main products generated from the TM data is a color composite using three of the six bands (excluding the thermal band). Because a total of 20 combinations can be made from the six TM bands taken three at a time (ignoring the permutations of bands and display colors), deciding which combination contains the most information on the basis of visual analysis can be difficult and time-consuming. The problem is more difficult with the 15 different ratios that can be generated from the six TM bands because they can be combined in 455 different ways (15 ratios taken three at a time). A technique called the Optimum Index Factor (OIF) developed earlier by one of the authors was used to rank the 20 possible combinations in the test sites studied (Chavez and others, 1982). The OIF technique ranks all the combinations possible based on the amount of correlation and the total variance present between the various data sets being used (e.g., six TM bands). The algorithm used to compute the OIF value for any subset of three bands is as follows:

$$OIF = \frac{\sum_{i=1}^3 SD_i}{\sum_{j=1}^3 |CC_j|}$$

where,  $SD_i$  = standard deviation for band  $i$   
 $|CC_j|$  = absolute value of the correlation coefficient between any two of the three bands being used (Chavez and other, 1982).

The combination having the largest OIF value should have the most information (as measured by variance) with the least amount of duplication. Often, the combinations that are within 2 to 3 ranking positions of each other appear similar and distinct feature differences cannot be detected. This is because there is little difference between closely ranked combinations as far as total information content is concerned. Table 2 shows the correlation matrix and the OIF rankings for several sites using the TM data.

The information shown in Table 2 was derived from TM data analyzed from a wide range of different test sites. The Death Valley data represents an arid environment; the Washington, D.C. area is an agricultural and urban setting; the San Francisco site includes agricultural, highly urban, and water settings; and finally, the Dyersburg, Tennessee site is mostly an agricultural setting. From the analysis of the data and the OIF rankings it was found that, in general, the three-band combinations that included one of the visible bands (TM 1, 2, or 3) and one of the longer wavelength infrared bands (TM 5 or 7) with TM 4 were usually ranked high by the OIF technique (i.e., having the most information with the least amount of duplication). This happens because of the high correlation that exists between TM bands 1, 2, and 3 and between TM bands 5 and 7 (see Table 2).

Additionally, in an attempt to maximize the amount of information contained in a final three-band/component combination and to minimize the information lost due to not using the other three bands, selective principal component analysis can be used (Chavez and others, 1982). Selective principal-component analysis involves using only highly correlated subsets or pairs of bands as input to principal-component analysis and not using all the bands simultaneously. Because the bands selected for principal-component analysis are so highly correlated most of the information is mapped into the first component. With the TM data processed so far, the subsets or pairs of bands used as input to selective principal-component analysis have been TM bands 1, 2, and 3 as one group and TM 5 and 7 as the second group. The first component of each of the two results is then combined with TM 4 to make a new data set that can be used as input for further processing (for example, contrast and edge enhancement for color compositing or input to digital classification).

In areas where this has been done between 96 to 98 percent of the information (variance) contained in the six bands was mapped to the new three-band/component combination. Silver Bell, Arizona was one of the sites processed by

TABLE 2

## TH SEVEN BAND CORRELATION MATRIX, DEATH VALLEY SUB-AREA

	1	2	3	4	5	*6	7
1	1.000	---	---	---	---	---	---
2	.975	1.000	---	---	---	---	---
3	.947	.983	1.000	---	---	---	---
4	.888	.942	.972	1.000	---	---	---
5	.579	.693	.745	.808	1.000	---	---
*6	.184	.249	.297	.277	.494	1.000	---
7	.503	.623	.704	.742	.945	.531	1.000
AVE	79.7	36.9	44.9	39.8	64.0	104.8	36.6
SD	18.5	10.6	14.6	13.7	24.1	7.9	14.3

QIF FOR DEATH VALLEY SUB-AREA USING 6 TH BANDS  
(TH6 - THERMAL BAND NOT USED)

RANK	**COMBINATION	QIF
1	(1,5,7)	27.75
2	(1,3,5)	24.94
3	(1,4,5)	24.74
4	(1,2,5)	23.64
5	(1,3,7)	22.00
6	(1,4,7)	21.80
7	(2,5,7)	21.77
8	(2,3,7)	21.47
9	(4,5,7)	20.73
10	(1,2,7)	20.64
11	(3,4,5)	20.62
12	(2,3,5)	20.20
13	(2,4,5)	19.83
14	(3,4,7)	17.45
15	(2,3,7)	17.13
16	(2,4,7)	16.76
17	(1,3,4)	16.68
18	(1,2,4)	15.26
19 (MC)	(1,2,3)	15.05
20 (HSS)	(2,3,4)	13.46

\*TH6 - THERMAL BAND

\*\*SIX BANDS COMBINED THREE AT A TIME GIVES 20 COMBINATIONS

## TH SEVEN BAND CORRELATION MATRIX, DYERSBURG, TN

	1	2	3	4	5	*6	7
1	1.00	---	---	---	---	---	---
2	.93	1.00	---	---	---	---	---
3	.94	.94	1.00	---	---	---	---
4	-.36	-.33	-.47	1.00	---	---	---
5	.42	.48	.43	.29	1.00	---	---
*6	.40	.42	.42	-.16	.50	1.00	---
7	.69	.72	.73	-.10	.89	.57	1.00
AVE	36.9	15.4	13.8	51.4	39.1	69.9	14.2
SD	3.9	2.8	4.8	13.7	11.2	3.0	6.9

QIF FOR DYERSBURG SUB-AREA USING 6 TH BANDS  
(TH 6 - THERMAL BAND NOT USED)

RANK	**COMBINATION	QIF
1	(1,4,5)	26.82
2	(2,4,5)	25.07
3	(4,5,7)	24.92
4	(3,4,5)	24.90
5	(1,4,7)	21.40
6	(2,4,7)	20.29
7	(3,4,7)	19.58
8	(2,5,7)	16.09
9	(1,3,4)	12.71
10	(1,2,4)	12.55
11 (HSS)	(2,3,4)	12.26
12	(3,5,7)	11.17
13	(1,5,7)	11.03
14	(2,3,5)	10.17
15	(1,2,5)	9.78
16	(1,3,5)	8.96
17	(1,3,7)	6.61
18	(2,3,7)	6.05
19	(1,2,7)	5.79
20 (MC)	(1,2,3)	4.10

TABLE 2 CONT'D

## TM SEVEN BAND CORRELATION MATRIX, WASHINGTON, D. C. SUB-AREA

	1	2	3	4	5	TH	7
1	1.00	-.01	-.01	-.01	-.01	-.01	-.01
2	.91	1.00	-.01	-.01	-.01	-.01	-.01
3	.83	.89	1.00	-.01	-.01	-.01	-.01
4	.27	.42	.34	1.00	-.01	-.01	-.01
5	.45	.56	.62	.67	1.00	-.01	-.01
TH	.24	.26	.32	.44	.55	1.00	-.01
7	.65	.72	.78	.84	.90	.89	1.00
AVE	60.90	24.80	26.10	40.90	52.10	116.50	20.20
SD	5.68	3.78	5.32	10.93	15.77	2.48	7.69

OIF FOR WASHINGTON, D. C. SUB-AREA USING 6 TM BANDS  
(TH6 - THERMAL BAND NOT USED)

RANK	**COMBINATION	OIF
1	(1,4,5)	23.46
2	(3,4,5)	19.64
3	(2,4,5)	18.61
4	(1,4,7)	17.70
5	(4,5,7)	17.00
6	(1,3,4)	15.24
7	(3,4,7)	15.12
8	(1,5,7)	14.61
9	(1,3,5)	14.08
10	(2,4,7)	14.04
11	(1,2,5)	13.18
12	(1,2,4)	12.82
13	(2,5,7)	12.52
14	(3,5,7)	12.51
15 (HSE)	(2,3,4)	12.20
16	(2,3,5)	12.06
17	(1,3,7)	8.26
18	(1,2,7)	7.52
19	(2,3,7)	7.03
20 (MC)	(1,2,3)	5.63

\*TH6 - THERMAL BAND

\*\*SIX BANDS COMBINED THREE AT A TIME GIVES 20 COMBINATIONS

## TM SEVEN BAND CORRELATION MATRIX, SAN FRANCISCO

	1	2	3	4	5	TH	7
1	1.000	-.000	-.000	-.000	-.000	-.000	-.000
2	.960	1.000	-.000	-.000	-.000	-.000	-.000
3	.933	.972	1.000	-.000	-.000	-.000	-.000
4	.348	.469	.548	1.000	-.000	-.000	-.000
5	.431	.542	.638	.856	1.000	-.000	-.000
TH	-.296	-.351	-.399	-.435	-.316	1.000	-.000
7	.561	.636	.718	.739	.829	-.344	1.000
AVE	59.20	22.90	22.10	25.30	29.80	91.00	14.10
SD	11.49	5.04	7.97	13.01	21.51	4.14	10.51

OIF FOR SAN FRANCISCO SUB-AREA USING 6 TM BANDS  
(TH6 - THERMAL BAND NOT USED)

RANK	**COMBINATION	OIF
1	(1,4,5)	28.14
2	(1,5,7)	23.93
3	(2,4,5)	21.69
4	(1,4,7)	21.28
5	(3,4,5)	20.81
6	(1,3,5)	20.46
7	(1,2,5)	20.17
8	(2,5,7)	18.96
9	(4,5,7)	18.60
10	(3,5,7)	18.33
11	(1,3,4)	17.75
12	(1,2,4)	17.15
13	(2,3,5)	16.48
14	(2,4,7)	16.03
15	(3,4,7)	15.74
16	(1,3,7)	13.58
17 (HSE)	(2,3,4)	13.55
18	(1,2,7)	13.00
19	(2,3,7)	10.54
20 (MC)	(1,2,3)	8.88

selective principal-component analysis and the results are shown in Table 3. The user does have to be careful to check

TABLE 1

TM SIX-BAND CORRELATION MATRIX FOR THE SILVER BELL AREA  
(TM6 = THERMAL BAND NOT USED)

	1	2	3	4	5	7
1	1.00					
2	.96	1.00				
3	.94	.97	1.00			
4	.83	.88	.92	1.00		
5	.75	.81	.85	.87	1.00	
7	.76	.81	.84	.87	.95	1.00

SELECTED SUBSET OF BANDS FOR "SELECTIVE" PRINCIPAL  
COMPONENT ANALYSIS BASED ON HIGH CORRELATION

- I. TM1            PC13            96.8% OF VARIANCE  
       TM2            PC23            2.6% OF VARIANCE  
       TM3            PC33            0.6% OF VARIANCE
- II. TM5            PC12            98.4% OF VARIANCE  
       TM7            PC22            1.6% OF VARIANCE
- III. USE PC11, PC12, AND TM4 AS THREE-COMPONENT DATA BASE  
       FOR ANALYSES, CLASSIFICATION, OR COLOR COMPOSITING.  
       CONTAINS A MINIMUM OF 98.3% OF SIX BAND VARIANCE.

the components/data not used to make sure that information of interest has not been isolated or mapped to one of the lower components. This did occur in the Silver Bell data where most of the information about an alteration zone of geologic interest was mapped to component number two of TM 5 and 7 (see figures 1 and 2). (This component also

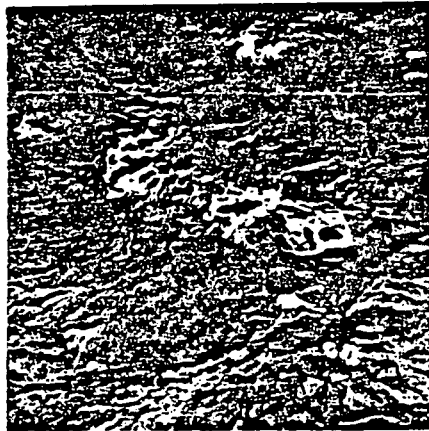


Figure 1a. Landsat 4 TM image of band 5 (1.55 to 1.75  $\mu$ m) with a linear contrast stretch of 9-108 (99 DN range). The Silver Bell copper mine is located in the center of the image.

happened to be highly correlated with the ratio of TM 5 to TM 7 (correlation coefficient of -.93)). Therefore, if the user is interested in one specific cover type instead of maximizing the information content over the entire area, selective principal-component analysis must be used with care, as should regular principal-component analysis. For information on principal-component analysis and other examples of its use, the reader is referred to Blodget and others (1978) and Pirkle and others (1980).

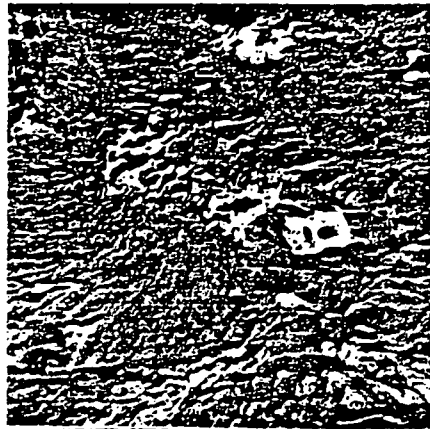


Figure 1b. Landsat 4 TM image of band 7 (2.08 to 2.35  $\mu$ m) with a linear contrast stretch of 4-57 (53 DN range).

Another method that can be used to reduce the amount of data that needs to be processed and analyzed is to use a combination of full- and compressed-resolution data sets. For many applications that require high-frequency or fine-detail information only one TM band in black and white with an edge enhancement is needed (for example, mapping of linear features). There are some applications where the added spectral information of TM over the MSS (7 bands vs 4 bands) is much more important than the increased spatial resolution (30 meters vs 80 meters). In a test conducted using the Death Valley TM data where the pixel size was compressed to 60 and 120 meters, there are color anomalies (discussed later in this paper) that were still visible on the 120-meter pixel size image made from TM Bands 1, 4, 5 but were not visible on the composite made from TM bands 1, 2, and 3 (natural color — NC) or TM bands 2, 3, and 4 (similar to MSS) at full resolution. In this case, the compressed data were complemented by an edge-enhanced black-and-white image of TM 4 at full resolution for fine-detail mapping.

Research is continuing into various ways to compress the digital data. Methods being compared include dropping pixels, averaging pixels, and averaging only where the first difference within the area to be compressed is small or using the pixel value within the area where the largest first difference occurs if it exceeds a set threshold. By doing this we hope to be able to reduce the image size but still retain full resolution in areas where it is needed.

At times, rather than being concerned about the large volume of data that exists for processing, a user wants to take data for a small area and enlarge it or integrate it with higher resolution data. Digital enlargement combined with spatial filtering can be used to accomplish this. A digital image (MSS, TM, or digitized photo) that is optically enlarged close to or past the limits supported by its pixel

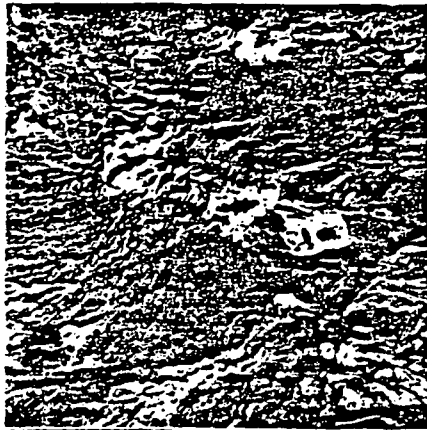


Figure 2a. Principal component number 1 of TM 5 and 7 with a linear contrast stretch of 9-120 (111 DN range). The amount of the total variance of TM 5 and 7 mapped to principal component number 1 was 98.36 percent.

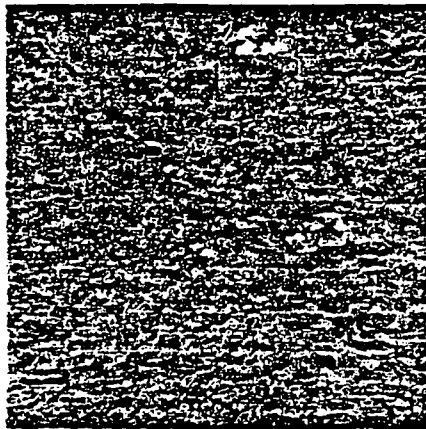


Figure 2b. Principal component number 2 of TM 5 and 7 with a linear contrast stretch of 69-89 (20 DN range). The amount of the total variance of TM 5 and 7 mapped to principal component number 2 was 1.64 percent. This image also shows a noise pattern contained in the TM data. The areas showing up in the darker tones correspond closely to an alteration zone previously mapped by the Geosat committee and JPL using TM simulator data.

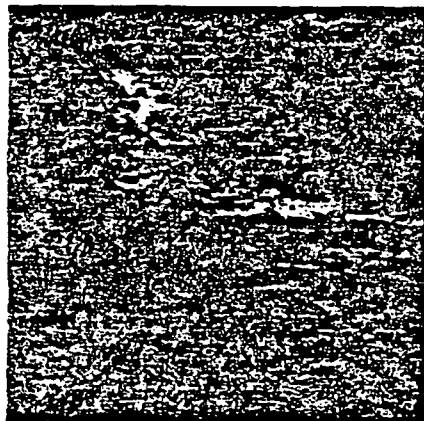


Figure 2c. This shows the results of the TM 5 to TM 7 ratio with a linear contrast stretch. Notice the correlation between it and principal component number 2 (correlation coefficient of  $-.89$ ).

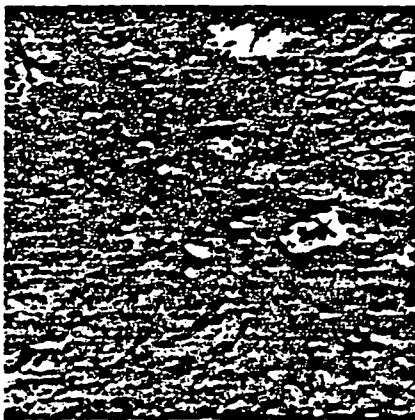


Figure 2d. Same image shown in figure 2b (i.e., principal component number 2 of TM 5 and 7) but with a small smoothing filter to suppress the noise and a harder contrast stretch to show the alteration zone area better.



Figure 2e. Same image shown in figure 2c (i.e., TM 5 to TM 7 ratio) but with a small smoothing filter to suppress the noise and to compare with principal component number 2 shown above. This ratio and principal component number 2 above have a correlation coefficient of  $-.93$ .

resolution will have a "blocky" appearance and often a fine screen pattern (caused by an anomaly in the hard-copy film writer) can be seen (see figure 3a). To solve this problem



Figure 3a. Portion of TM band 5 image showing the Washington, D.C. Dulles airport area. This image represents the original data without any digital enlargements. The blocky appearance and screen pattern discussed in the text can be seen in this product, especially with a 8X lens.

we have used a method developed by one of the authors in his investigation of geometric resampling. The process involves the combination of digital enlargement by pixel duplication followed by spatial filtering for smoothing and, if necessary, edge enhancement. The main reason that an image appears blocky and the screen pattern becomes visible is that when an image is optically enlarged to a scale that is close to or past the limits supported by its pixel resolution, the individual pixels become so large that they no longer interact visually to create patterns and features. Each pixel starts to be viewed separately and is seen as an individual feature or pattern. To minimize this problem the number of pixels in the image is increased so that ~~the~~ less optical enlargement is needed to get the image to the desired scale.

resulting in a smaller final pixel size. However, if only pixel duplication is used the image will still look blocky at the desired scale (see figure 3b). The blocky appearance



Figure 3b. Same image shown in figure 3a but with a 3X digital enlargement. The enlargement was done using simple pixel duplication so that one pixel became a 3 by 3 array where all nine pixels were assigned the same digital value.

may be more obvious than in the original image because one pixel becomes an  $N \times N$  pixel array with the same brightness (for example,  $5 \times 5$  in the case of a 5X digital enlargement).

To eliminate this effect a smoothing filter needs to be applied to the data. The size of the filter is critical (see Figure 3c), and must be equal to the size of the digital enlargement in order to not over- or under-smooth the data. Also, by using a smoothing filter that is the same size as the digital enlargement, the values of the pixels at the center of the enlarged arrays will not change (for example, pixel at middle of  $5 \times 5$  array using a 5X enlargement). This has the same effect as separating the original pixels by the digital enlargement factor and then using a two-dimensional smoothing/interpolation technique to fill in the missing holes (i.e., resampling).

Digital enlargement by pixel duplication can be considered a form of nearest-neighbor resampling when applied to an image that already has the desired geometric characteristics. The two-dimensional smoothing filter is a form of interpolation similar to bilinear or cubic convolution.



**Figure 3c.** Same image shown in figure 3b but with a 3 by 3 smoothing filter applied to the data. It is important that the size of the smoothing filter be equal to the size of the digital enlargement in order to not over or under smooth the data.

This method is more straightforward and computationally efficient than resampling the original image using cubic convolution to a higher resolution. Also, the procedure can be repeated with different enlargement factors if the user desires several different scales or sub-areas from the same image.

This enlargement technique has been used on both Landsat MSS (5X) and TM (3X and 7X) data with very encouraging results. The MSS data held up well at a scale of 1:100,000 and the TM at a scale of 1:50,000. The method also helped suppress some of the random noise effects often seen in enlarged digital images and produced more homogeneous patterns (this can be seen by color coding the before and after images using the same color table). The method expands the pixel spacing and interpolates a smooth transition between the brightness values of two pixels instead of having an abrupt change. This is similar to what bilinear, cubic convolution, or restoration does when resampling MSS data to 50-meter pixels. In the 3X enlargement of TM data the resultant image looked slightly defocused. To reduce this apparent defocusing algorithm an edge enhancement was applied to the data using a kernel size that was approximately twice the digital enlargement (that is, digital

enlargement of 3x3 with an edge enhancement kernel of 7x7, see figure 3d). In the MSS and TM examples which used a 5X and 7X enlargement followed by 5x5 and 7x7 smoothing



**Figure 3d.** Same image shown in figure 3C but with a 7 by 7 edge enhancement. When the digital enlargement is small (e.g., 3X) the resultant image can appear slightly out of focus so that an edge enhancement will be needed to sharpen-up the image.

filters, the resultant images did not look as defocused. This may be due to the increased number of new pixels placed among the original pixels thus reducing the incremental brightness transition between pixels. The products generated by this method will be compared with some made by directly digitally enlarging an image using cubic convolution resampling.

The image analyses comparing the TM bands which are similar to the MSS bands (TM 2, 3, and 4) with other TM band combinations, which include some of the new additional spectral bands, indicate that there is new or more information in the TM data set. To evaluate only the spectral differences and not be influenced by the difference in spatial resolution, the comparisons have been made using only the TM and not the MSS data (this will be done in future work). TM bands 1, 2, and 3, which approximate the visible part of the spectrum and generates a composite that has colors close

to natural color, were also compared with the TM 2, 3, and 4 combination. Table 2 shows that both the natural-color and MSS-equivalent band combinations are usually ranked quite low by the OIF method.

Visual analyses of several TM band combinations in the Death Valley image have produced some interesting results. There are some surficial anomalies that are readily apparent in this area on TM band combinations 1, 5, 7 and 1, 4, 5, combinations ranked 1 and 3 by the OIF (see Table 2). On TM band combinations 1, 2, 3 and 2, 3, 4 (natural-color and MSS-equivalent), there are no signs of these same anomalies. Several of these anomalies were field-checked and once identified, it was correctly predicted that similar anomalies would appear in the same TM combinations in an image covering an area just north of Flagstaff, Ariz. These areas have also been field-checked, and the results of that investigation are currently being prepared for publication.

Further analyses of some Death Valley images have identified another potential use of the TM band combinations. On some TM band combinations it appears that there may be a relationship between soil moisture/ground water depth and the colors seen on the resultant image product. In the desert Death Valley image TM band combinations that include either TM bands 5 or 7 or both portrayed as green and red, respectively, in color composite, seem to map areas influenced by high soil moisture or shallow ground water in various shades of blue. Several playas in the image appeared as light- to medium-blue while others remained white. Also, drainage areas along the playas were usually darker than their surrounding light-blue areas, indicating lower brightness levels in TM bands 5 and 7. Snow on the mountains surrounding the Death Valley area appeared in the same image products as very dark blue, indicating again low brightness values in TM bands 5 and 7.

One possible explanation is that TM 1, a visible band not affected by water absorption, was exposed through the blue filter and TM 5 and TM 7 were exposed through the green and red filters, respectively. Because TM 5 and TM 7 are affected by water absorption, areas of higher soil moisture will have lower digital values than their surrounding areas with lower soil moisture. Areas appear in shades of blue depending on the amount of soil moisture because the brightness values are less in TM 5 and 7 (used as green and red in the color composite) while they stay relatively constant with the surrounding areas in TM 1 (used as blue in the composite and not affected by soil moisture). This color difference can be seen less clearly in composites made with TM 1, 2, 5 and TM 1, 2, 7.

It must be pointed out that these soil moisture correlations are only preliminary, and no field calibrations have been possible due to data delivery problems encountered with the TM system. Most investigators are working with data collected during time frames that could not be predicted. The current observations do warrant further investigation when the new TM system is launched, offering opportunities for appropriate field calibration.

## SUMMARY

The techniques of OIF ranking of band combinations, image enhancement, and spatial compression have been used to process and analyze efficiently large volumes of TM data. From the digitally compressed data and other analyses, it seems that there are some applications where the added spectral information in the TM data is more important than the increased spatial resolution, as compared to the MSS. Also, digital enlargement and smoothing algorithms have been used successfully to generate large-scale TM and MSS products and to merge data sets with different resolutions.

The image analyses done under this project indicate that there is new information in the added TM bands that was not provided by the MSS system. The potential use of TM data to extract information about soil moisture and ground-water depth warrants further research and future data collection where field calibration is possible.

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